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Electrical Testing of Mockup of 15-mW RTG from Laboratory RFNC-VNIIEF, Russia

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Electrical Testing of Mockup of 15-mW RTG from Laboratory RFNC-VNIIEF, Russia

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Abstract

This report describes electrical testing at Sandia National Laboratories/New Mexico of a mockup of a 15-mW, 50-year-design-life radioisotopic thermoelectric generator designed and constructed in Russia. This mockup is identical to the plutonium-fueled versions except for installation of an electric heater in place of the plutonium fuel capsule. Results are presented of measurements of power output and other characteristics at various heater powers corresponding to beginning and end of design life. Output over a range of load resistances was measured in order to characterize the low-temperature-difference thermopile used in this RTG.

Summary

Electrical testing was done on an electrically heated mockup of a plutonium-fueled radioisotopic thermoelectric generator (RTG) designed for a long-term surveillance application. The design specifications include an electrical output of 15 mW or greater at 3 V at beginning of life, and 10 mW or greater at 3 V after 50 years of operation, both at 25°C ambient. Measurements were made of electrical output at temperatures of 50°C, 25°C, and –50°C over a range of load resistances from 1 Ω to 1000 Ω, plus open circuit. Measurements showed that the output power of the mockup at beginning of life was approximately 15% lower than the design specification indicated, and 35% lower at end of life. Peak power output at a heater power corresponding to beginning of life was 13.2 mW at 2.7 V. At 3 V, the power output was 12.6 mW. At a heater power corresponding to 50 years of operation, maximum power output was 6.5 mW at 1.84 V.

An extrapolation of the data showed that 3-V output at a heater power corresponding to 50 years of operation would be achieved at a load resistance of 3340 Ω, with an output power of 2.7 mW. A calculation based on decay rates of plutonium and thermoelectric principles indicates that an RTG with 15 mW beginning-of-life output would decrease to an output of approximately 6.8 mW after 50 years, so it appears that the specification of 10 mW output at 50 years is inconsistent with a specification of 15 mW at beginning of life. Complete voltage and power load data are presented.

I. Principles of RTG Operation

An RTG is a simple device that consists of a heat source fueled by the heat of decay of a radioactive isotope, and a thermoelectric device, often referred to as a thermopile, that converts heat into electric power. The thermopile is usually a series of semiconductor junctions heated at one end by the heat source, with the other end in contact with the case of the RTG, which is at a lower temperature. RTGs are highly reliable, long-life power sources, with applications in spacecraft, surveillance devices, and weapons systems. Design output electric powers range from less than one milliwatt to hundreds of watts, depending on the applications.

Compared with chemical electric power sources, RTGs are low power for their weight and size but have very high energy because of their long lifetimes. Efficiency of conversion of the heat of decay to electric power is low, typically less than three percent. Improvement of this efficiency is the primary goal of RTG development, with the focus being on new semiconductor thermoelectric materials.

The operation of the thermopile depends on the Seebeck effect,[1,2] in which a conductor whose ends are at different temperatures will have an electromagnetic force (EMF), or electric potential difference between those ends. This EMF occurs whether or not there is current flowing in the conductor. A potential difference does not produce power unless current flows in a closed circuit. Different metals or semiconductors have different Seebeck coefficients and, therefore, different EMFs for a given temperature difference. As a result, a closed circuit can be made to allow current flow, producing power in a resistive load.

It is important to note that in an RTG, the output of the thermopile is a *voltage* that is proportional to the temperature difference between the heat source and the RTG case or heat sink and the heat source temperature is a nearly linear function of the heat source power, which decreases exponentially with the decay of the radioactive isotope. The thermopile output *power* is proportional (for a given fixed load resistance) to the square of the thermopile output voltage. This means that the RTG electrical output power is approximately proportional to the square of the heat source power. If the heat source power decreases by a factor of two, the RTG electrical output power decreases by approximately a factor of four.

In addition, different metals or semiconductors connected together form a junction. When a current flows in the circuit, there is an entropy change in the electrons flowing across the junction because of the difference in chemical potential of the two conductors. This entropy change produces heating or cooling, depending on the direction of current flow. This is the Peltier effect, and it is the principle used in semiconductor junction refrigeration systems.[3,4] There is also a Thompson effect, which involves entropy and temperature change of charge carriers flowing in a temperature gradient. The Thompson effect is relatively small in devices of interest. The Peltier effect, while not dominant, must be taken into account in power generating systems.

The most common radioisotope fuel is ^{238}Pu, which has a convenient half-life of 87.7 years. The decay products are ^{234}U and ^{4}He, with a power production of 0.56 W/g. The isotope is generally used as PuO_2, rather than as metallic Pu. Production of helium gas during the decay requires either a pressure containment capsule for the fuel or a way to vent the helium without plutonium escape. Unmanned spacecraft usually vent the helium,[5] while terrestrial applications use pressure vessels because of safety considerations.

II. Description of the Mockup RTG Tested

The RTG tested is a mockup of a device intended for use in a long-term surveillance application, and is designed to have an operating life of 50 years. The mockup is intended to duplicate the plutonium-loaded RTG except for the substitution of an electrically-powered heater for the plutonium capsule.

The principal specifications of the plutonium-fueled RTG, and of the RTG mockup tested here, are contained in Appendices I, II, and III. Appendix I is the service manual for the RTG mockup, and it is short enough to be reproduced here in its entirety. Appendix II is from the report of the RTG prototype tests, and Appendix III is from the final report on the design and development of the RTG. Because of the length of these two reports, only pages 1–8 of each are included here. Appendices I, II, and III were reproduced from available copies, and the reproduction quality is poor. These pages include specifications pertinent to the measurements and evaluation of the RTG mockup done at Sandia National Laboratories and reported here.

The RTG mockup contains an electrical heat source (intended to simulate the plutonium-fueled heat source), a semiconductor thermopile that is composed of $Bi_2Te_3 - Bi_2Se_3$ (n-material) and $Bi_2Te_3 - Sb_2Te_3$ (p-material). This bismuth telluride thermopile is a relatively advanced type that is optimized for low-temperature (<200°C) operation. A thermocouple is installed in the mockup to measure the temperature at the heat-source/ thermopile junction. The heater input and thermopile output are connected via a four-conductor plug in the base of the RTG, and the internal thermocouple connections are made through two electrical feedthroughs in epoxy-sealed holes drilled in the base.

The operation manual (referred to as Service Manual in the manual title) is very brief, and is reproduced in Appendix 1. The electrical specifications for the mockup are given in the Service Manual as 15 mW output at 3 V, with an applied heater power of 1.3 W to 1.4 W, at a nominal heater supply voltage of 5.7 V to 5.8 V. The operating temperature range is given as –50°C to +50°C. An electrical output specification of 15 mW at 3 V implies a load resistance ($V^2/P = R$) of 600 Ω.

Appendix II, RTG Prototype Tests, Section 4.3, describes testing of two plutonium-fueled prototypes of this RTG. Prototype serial number 01 is described as having a plutonium heat source of 1.43 W, and a "semiconductor thermoelectric battery," referred to here as a thermopile, having 245 working couples of the 250 in the thermopile. Prototype serial 02 has a heat source of 1.38 W and 235 working couples of 250. It is not known how many working couples are contained in the RTG mockup. Electrical tests on the two prototypes were done with a variable resistance load that was adjusted to maintain the thermopile output voltage at 3.0 V. Under these conditions, the output of serial No. 01 prototype was 17.1 mW with a measured hot junction temperature of 130.5°C, and the output of serial No. 02 was 15.7 mW with a hot junction temperature of 125°C. Other details are described in Appendix II.

The Final Report in Appendix III, Section 1.1, specifies that the minimum RTG electric power at the beginning of service life is 0.015 W at 3.0 V, and at the end of service life (defined as 50 years), the minimum electric output power is 0.010 W at 3.0 V, a decrease to 67% of initial power. A calculation of the decay of ^{238}Pu (half-life 87.7 years) using the formula in Appendix II, Section 4.4 (which is a standard isotope decay formula), shows that 67% of the plutonium remains after 50 years, meaning that the heat source power is then 67% of its initial value. As discussed above, the expected electrical output from the thermopile after 50 years is approximately $(0.67)^2$, or 45%, approximately 0.00675 W, rather than 0.010 W, so there appears to be an inconsistency in the specifications.

The internal thermocouple type is not described in the service manual supplied with the RTG mockup, but was verbally described as a "chromel-copel" type. Copel is a resistance material used for heater elements, and it appears to be essentially identical to constantan. The thermocouple was, therefore, tentatively assumed to be chromel-constantan, commonly referred to as a type E thermocouple. A measurement of the resistance of the internal thermocouple showed 10 Ω between the feed-through terminals, indicating a high probability that a 10 Ω resistor was installed inside the RTG case in series with the internal thermocouple. A series resistor is used when a current-sensing device such as an analog moving-coil meter is used to indicate temperature. A thermocouple pair produces an output voltage that is proportional to temperature difference between the measuring junction and a reference junction, and the series resistor is chosen so that the total external resistance (thermocouples plus resistor) is a known fixed value. The current in the meter is then proportional to the measurement thermocouple voltage. Most digital meters and data loggers use high-impedance operational amplifier inputs or voltage-nulling bridges with analog-to-digital converters, eliminating the need for the external resistor.

III. Experimental Plan and Setup

The primary purpose of the measurements was to compare the thermopile output with the specifications listed in the operating manual. The electrical output was specified only at an ambient temperature of 25°C, and at a heater power of 1.4 W, the initial thermal output of the plutonium heat source installed in a production unit. Since the unit is intended to operate for 50 years, the output was also measured at a heater power of 0.95 W, calculated for 50 years of plutonium decay. Because of interest in the operation of the barium telluride thermopile at low-temperature differences, output was also measured at a heater power of 0.65 W, equivalent to 100 years of decay. These measurement were made at external temperatures of –50°C, 25°C , and 50°C. Load characteristics of the barium telluride thermopile are also of interest, so the measurements were made with load resistances of 1 Ω to 1001 Ω in 100 Ω increments, and at open circuit.

Two type K (chromel-alumel) thermocouple junctions were fabricated and epoxied to the RTG mockup case, one centered on top and one on the bottom center at the assumed location of the thermopile thermal contact with the case. A plug to fit the four-pin connector mounted on the RTG mockup base was not available, and connections were made using individual female pins from a standard connector. The set of four wires was clamped together and to the plug shell for strain relief. Connections were also made to the internal thermocouple, using type E extension wire fabricated from type J and type K extension wire. The RTG mockup was operated at all times mounted on its supplied tripod stand, with the connectors down (side and top views shown here).

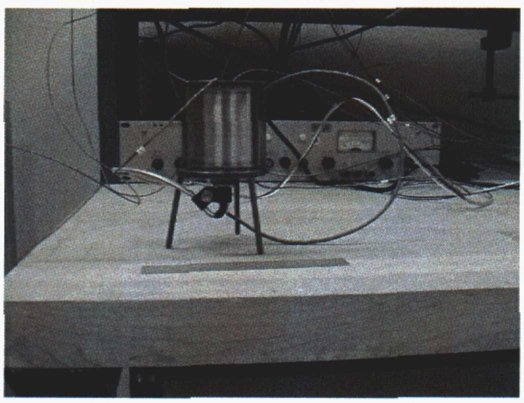


Figure 1. RTG on its stand, showing cables and connected thermocouples.

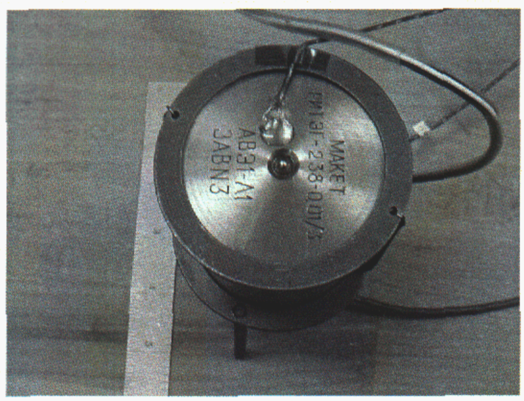


Figure 2. Top view of RTG showing attached thermocouple.

The supply used to power the heat source is an Agilent E3630A Triple Output supply, with 3-digit output voltage metering. A 1-Ω, 5-W resistor was placed in series with the heater and the voltage drop recorded to provide a measure of the heater current. The 1-Ω resistor was measured and found to be 0.99 Ω. The variable load resistor was fabricated using a ceramic rotary switch and ten 100-Ω metal-film 1% resistors. The 1-Ω resistor, which is the minimum resistance load, is a 5-W 3% unit. The last switch position is open circuit, so load resistance steps are 1 Ω (near short circuit) to 1001 Ω in 100 Ω steps, with a final open circuit (infinite resistance) load. Voltage across the load resistance was recorded and also monitored with a five-digit Hewlett-Packard 3466A Digital Voltmeter. Testing was performed with the RTG mounted on the stand shown, which was supplied with the RTG.

Data were recorded on an Omega RD840 eight-channel datalogger. This datalogger is designed for thermocouple as well as voltage inputs and has internal electronic reference junctions and compensation for all common types of thermocouples. The datalogger has a graphics screen display, and records data on a 1.4 Mb floppy disk for transfer. The datalogger is programmable and, for these measurements, was set for one recording of all channels each minute.

Measurements were made with the RTG mockup located in a Tenney Environmental type TJR environmental chamber. The experimental setup and the RTG in the environmental chamber are shown in Figures 3 and 4.

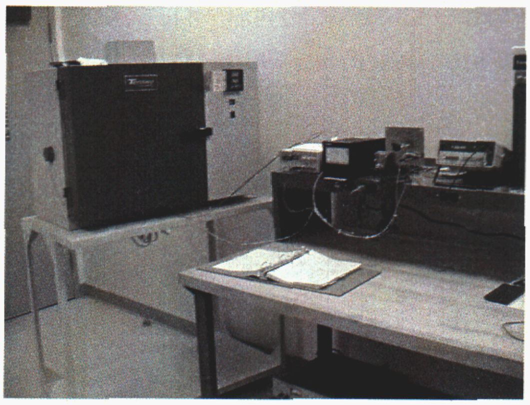


Figure 3. RTG evaluation setup, with (from left) environmental chamber, power supply, datalogger, load R, and DVM.

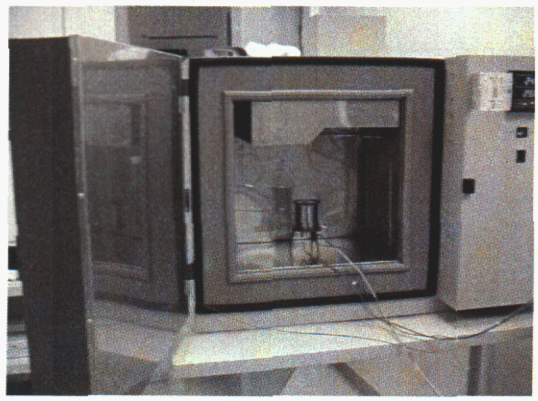


Figure 4. RTG in environmental chamber.

IV. Measurements and Analysis

Seven channels were recorded on the Omega datalogger: top external thermocouple, bottom external thermocouple, internal thermocouple, heater voltage, heater current (voltage across the 1 Ω resistor in series with the heater supply), thermopile output voltage, and oven temperature (measured by a type K junction suspended in the oven).

Changes in oven temperature or heater voltages were made with a 601 Ω load applied to the thermopile. After the thermopile output voltage stabilized, the load resistance was varied from 1 Ω to 1001 Ω, in 100-Ω steps, with approximately three minutes at each step, then to open circuit for approximately 5 minutes, and then to 601 Ω for approximately 15 minutes.

A plot of output power at the various temperatures and heater powers vs. load resistance is shown in Figure 5. Peak power at 25°C occurs at a load resistance of 400 Ω to 500 Ω, rather than the predicted 600 Ω. Peak power at 1.39-W heater power and 25°C is 13.1 mW, approximately 87% of the design output of 15 mW. At end-of-life heat source power of 0.95 W, output power decreased to a peak of 6.5 mW.

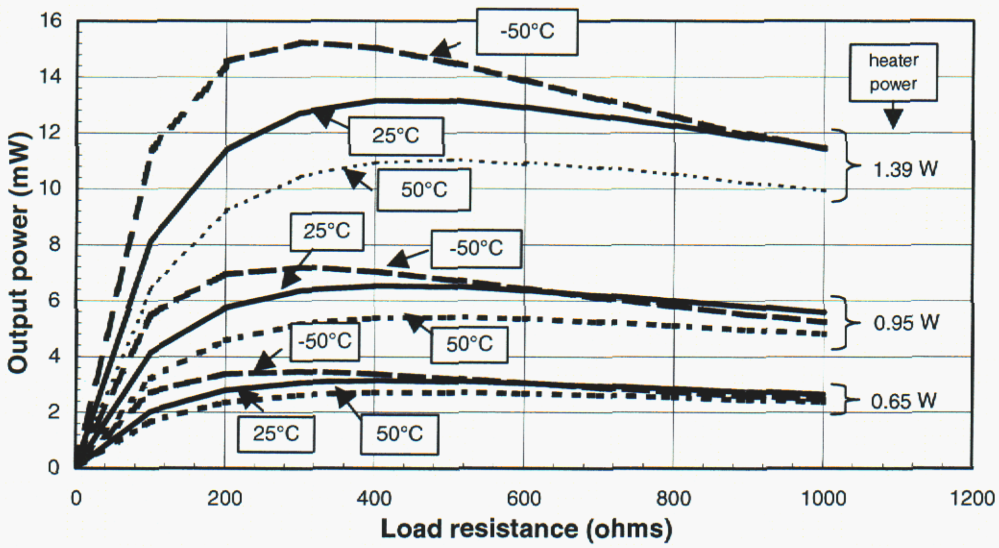


Figure 5. Output power vs. load resistance at three heater powers and temperatures.

A similar plot of the thermopile output voltage is shown in Figure 6. There is no indication in the mockup RTG operating manual of minimum usable output voltage, but the design voltage output is 3.0 V. This voltage in the mockup is achieved (at 25°C and 1.39-W heater power) at an interpolated load resistance of approximately 720 Ω, where the output power is approximately 12.5 mW.

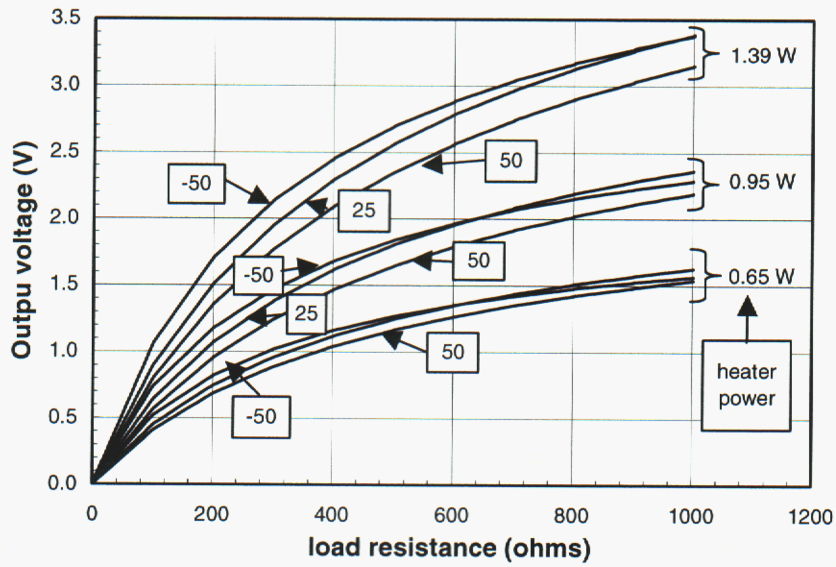


Figure 6. Thermopile output voltages vs. load resistance for the operating ranges tested.

By the end of life at 50 years, corresponding to a 0.95-W heater power (at 25°C), the measured output power peak at 500 Ω load is 6.5 mW at a voltage of 1.84 V. Note that the output power is not a linear function of the heat-source power. This is expected, since as discussed above, the output power is approximately proportional to the square of the output voltage, and so to the square of the heater power. Nonlinearities reduce the power dependence, and at a constant load of 400 Ω, the output power measured at the three heater powers is a good fit to $P_{out} = 7.15\ P_{htr}^{1.85}$.

The thermopile circuit can be approximated by the simple circuit shown in Figure 7, and predictions made of outputs at various heat source powers and load resistances. The thermopile is approximated by a voltage source V_S in series with a source resistance R_S. The external load resistance applied is R_L, and the voltage output is V_O. In a common linear power source, V_S would be the open circuit voltage V_{OC}, i.e. with R_L = [infinity], and $R_S = V_{OC} / I_{SC}$, where I_{SC} is the short circuit current, $R_L = 0$. Because of the nonlinearities of the thermopile, V_S and R_S were calculated from the 200-Ω and 1000-Ω load data at each of the three test temperatures and three heat source powers (see the graphs above). Table 1 shows the results of these calculations.

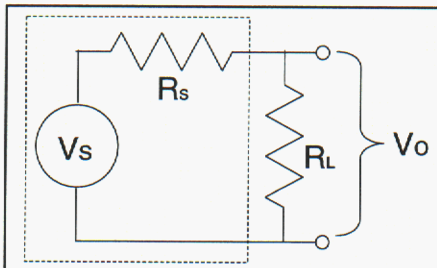


Figure 7. Thermopile circuit.

Table I. Measured and calculated RTG outputs.

equiv age, years	test temp, °C	calc source V	calc source R	calc max pwr (mW)	calc load R for 3 V	calc mW, 3 V out	meas pwr (mW)	load R for max pwr (ohms)
0	50	4.72	498	11.21	866	10.39	11.1	500
0	25	4.93	455	13.34	708	12.71	13.2	450
0	-50	4.49	329	15.36	660	13.64	15.2	300
50	50	3.24	479	5.48	5957	1.51	5.4	500
50	25	3.39	435	6.61	3340	2.69	6.5	450
50	-50	3.00	310	7.24	inf	0.00	7.2	300
100	50	2.24	456	2.76			2.7	450
100	25	2.31	420	3.17			3.1	400
100	-50	2.03	296	3.48			3.5	300

The first two columns are the thermopile calculated source voltage and resistance for each temperature/heat source power, and P_{peak} is the calculated maximum power available at that source voltage and resistance. The load resistance R_L for maximum power is equal to the source resistance R_S (see the circuit above). These calculated powers are within 1% of the measured peak powers taken from the recorded data. Because the power output of the RTG is specified at 3 V (Appendix I), the load resistance needed to achieve 3 V was calculated, and the calculated power available at 3 V is also listed. It can be seen that at 50 Y heat source age, 3 V will be barely reached at high load resistance, and the output power will be less than 3 mW.

Attempts to measure the heat source temperature with the internal thermocouple were not successful. Comparison with an external type E thermocouple at various external temperatures (no heater power) produces different outputs. Whether this was an effect of the series resistor incorporated in the internal thermocouple on the Omega measuring system, which may use an electronic null-balance system that may be disrupted by a large external resistance, or some other effect, is not known. There were also occasional abrupt shifts in the indicated temperature of the internal thermocouple during changes in oven temperature. However, the internal thermocouple output was recorded, and though the absolute temperature indication is not useful, the relative changes produced some interesting results.

The curves shown in Figure 8 are the relative temperature as measured by the internal thermocouple, and the current flowing in the thermopile at an external temperature of 25°C and a heater power of 1.29 W, as the load resistance is changed during the testing. The Peltier cooling effect of current flow in the thermopile can be clearly seen, as the current varies from the initial peak when the load resistance was switched from 600 Ω to 1 Ω, decreasing as the load resistance is increased. The current is zero for approximately 15 minutes (open circuit), and the temperature as measured by the internal thermocouple rises steadily during this time. Note that this temperature measurement indicates only direction of change and is not an absolute temperature measurement. It is not clear how much the temperature would have increased, as there is considerable time lag between the change in current and the change in temperature.

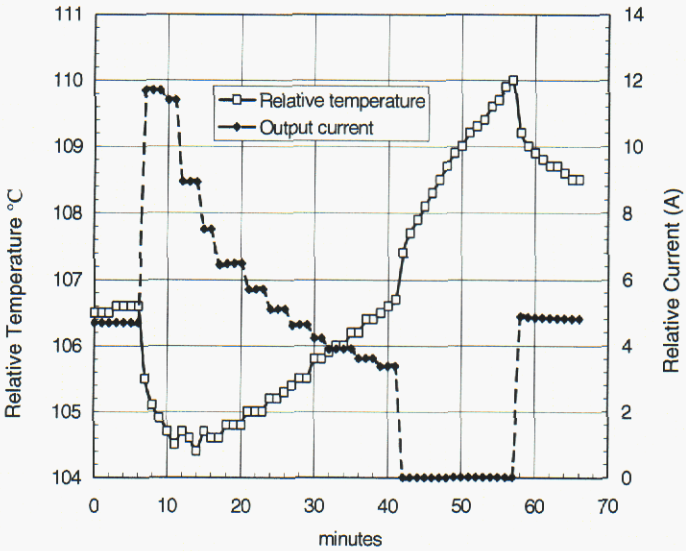


Figure 8. Change in temperature of the thermopile heat source junction and change in load current as the load resistance is varied during testing.

An indication of the time required for temperature stabilization after the heater is switched on can be seen in Figure 9. This measurement was taken at an ambient temperature of 50°C and a heater power of 0.95 W. The load resistance during heater warmup was 600 Ω. After the output voltage stabilized, the load resistor sequence was begun. The time lag in the cooling effect can be seen in the voltage sag at each load step, and the increase with time in the output voltage while on open circuit (the peak between 184 and 190 minutes).

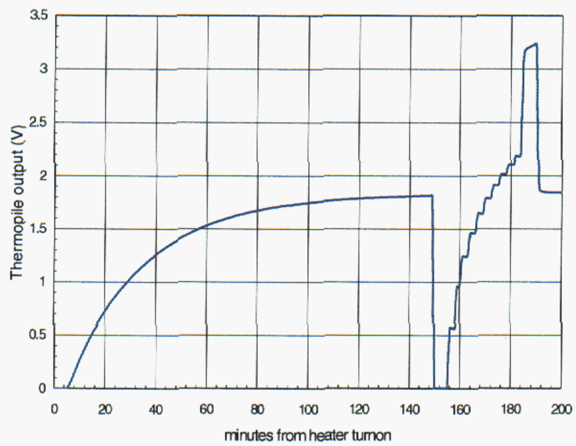


Figure 9. RTG stabilization time after application of heater power.

V. Conclusions and Discussion

Measurements of the RTG mockup showed an output electrical power that was approximately 15% lower than the device specifications at the specified heater power of 1.4 W and at 25°C ambient temperature. Measurements of the two plutonium-fueled RTG prototypes described in Appendix II, RTG Prototype Tests, Section 4.3, show electrical outputs of 17.1 mW and 15.7 mW. Both are described as having several couples inoperative of the 250 couples in the thermopiles. The low electric power output of the mockup might have two causes: (1) the thermal contact between the electric heater and the thermopile may have a higher thermal resistance than in the plutonium-fueled prototypes and (2) there may be more inoperative couples in the thermopile. Connections in the thermopile must be made at the time of manufacture to bypass inoperative couples, or some couples may be shorted in the process of forming connections. We performed the testing with the RTG mounted on the stand supplied. Thermal connection of the RTG base to a heat sink might also improve output somewhat.

A more serious concern is the discrepancy between specified and measured output powers at the heater power corresponding to 50 year service life. The measured output corresponds very well with the output calculated for the 50-year-life heater power, so it appears that 15-mW electrical output at beginning of life is inconsistent with a requirement for 10-mW, 3-V output at 50 years. There seem to be two possible solutions to this difficulty: (1) increase the amount of fuel by approximately 33% to provide more than 20-mW initial output or (2) change the specification, making up for the power loss with improved electronics.

References:

1. *CRC Handbook of Thermoelectrics*, D.M. Rowe, ed., CRC Press, New York, 1995, pp. 7-25.

2. Lifshitz, E.M., Landau, L.D., *Electrodynamics of Continuous Media,* Addison-Wesley, 1960, pp. 104-110.

3. Lifshitz and Landau, ibid.

4. See, for example, descriptions and data for commercial units from Tellurex Corporation, Traverse City, MI, or Melcor Corporation, Trenton, NJ.

5. Bass, John C., HiZ Technology, Inc. XVIII Intl. Conf. on Thermoelectrics, *Preliminary Development of a Milliwatt Generator for Space,* May 1998, Nagoya, Japan.

APPENDIX I
RTG Mockup Service Manual

RFNC-VNIIEF
Russia, 607190 Nizhni Novgorod region
Sarov

MOCKUP

RTG-238-0,01/3

Service manual
АВЭ1-Л1РЭ

1 Overview

The RTG-238-0,01/3 АВЭ1-Л1 mockup (RTG mockup) is designed to support remote monitoring system during its work demonstration.

2 Design features and specifications

1 Output electric power, W (ambient temperature 25°±10° and output voltage 3±0,1V)	0,015
2 Nominal power of thermoelectric heater, W (nominal supply voltage 5.7…5.8 V)	1,3…1,4
3 RTG mockup dimensions, mm diameter height	 60 97,7
4 Mass with a stand, kg	0,58
5 Insulation electrical resistance between electric connector contacts and RTG mockup basis, kOhm	20 minimal
6 Time for nominal operating, hour	4

3 Set of equipment

The list of equipment is tabled below

Table 3.1

Description	Quantity	Abbreviation	Dimensions mm.	Mass, kg	Packaging
1 RTG-238-0,01/3 mockup	1	АВЭ1-Л1	Ø60 H=97,7	0,440	Transportation packaging
2 Electrical cable	1	-	3000	0,088	Transportation packaging
3 Transportation packaging	1	6-5714.000	160×160 ×260		
4 Stand	1	6-5714.000	-	2,6	Transportation packaging
5 Operation manual	2*	АВЭ1-Л1РЭ		0,123	

Note. * One copy in English and one in Russian.

4 RTG design and pre-starting procedure

4.1 RTG mockup design

RTG mockup is a monoblock unit without mechanical fastening to the load. During performance demonstration the RTG mockup is installed into the stand which is included into the set of equipment.

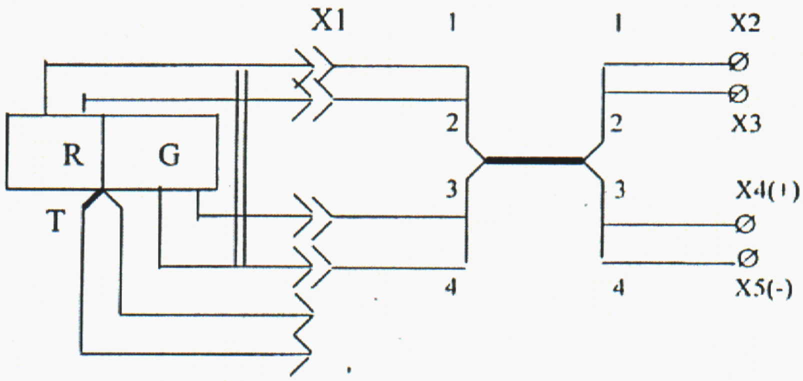
A RTG mockup consists of a steel cylindrical casing with a lid and basing, where a RHS (radionuclide heat source) mockup with resistive heat source is installed as preliminary heat source, and a STB (semiconductor thermoelectric battery) as a converter of thermal energy into electric energy.

Free space is filled with thermal insulation. RTG mockup inner space is filled with xenon up to atmosphere pressure.

RHS mockup and STB electric leads are brought out through the contacts 1,2 and electric connector plug 3,4, located on the RTG mockup basing. RHS mockup is supplied from the external electric source of 5.7... 5.8 V.

To control temperature of STB hot junction (if necessary) A thermocouple T is installed between the RHS mockup and STB, wires of which are brought out through the sleeves at the bottom of the RTG mockup.

RTG mockup circuit diagram



Abbreviation	Description	Q.
G	STB	1
R	RHS mockup	1
X1	Plug PC4 TB ABO.364.047TY	1
X2,X3,X4,X5	Electric cable terminals	4
T	Thermocouple	1

4.2 Pre-starting procedure

Take the RTG mockup with the stand out of the transpiration packaging. The RTG mockup should be removed from the packaging by seizing the bottom of the stand or carefully the casing.

Remove the technological cap from the RTG mockup electrical connector plug and connect with electrical cable.

Connect X2 and X3 terminals of electrical cable up to the power source of RHS mockup. Connect X4 and X5 terminals up to the remote monitoring system with total resistance of ~ 600 Ohm.

Set voltage of 5.7 V at the RHS mockup using power source to provide RHS mockup thermal power of 1.32 W.

Keep the system for ~ 4 hours. After this the RTG mockup is in operating mode providing voltage of 3±0,1V and electric power of 0.015 W.

After work completion switch off the power source, dismantle the system, and put the technological cap onto the plug of RTG mockup electric connector.

Put the RTG mockup into the transportation packaging in the sequence inverse to the unpacking procedure.

5 Application

5.1 Operating restriction

RTG mockup is serviceable during storage and transportation after the following environmental impacts:

- relative air humidity of 98% and temperature up to 35°C;
- temperature change -50°C to +80°C;
- change of atmosphere pressure 50 kPa up to 150 kPa.

RTG mockup operating temperature -50°C up to +50°C, and at relative humidity up to 98% at a temperature up to 35°C.

5.2 Safety requirements

5.2.1 There is no special safety requirements for a RTG mockup.

5.2.2 Electrical safety requirements - in accordance with "Electrical device operation rules" and "Safety rules during electrical device operation".

6 Storage and transportation

A RTG mockup should be stored with installed cap at a connector in a packaging, in enclosed space, including non-heating rooms, at an ambient temperature -50°C up to +50°C and at a relative humidity of 98% up to 35°C.

A RTG mockup may be transported in the packaging by any kind of air and surface transport without any speed, height and distance constraints.

The packaging should be in vertical position during storage and transportation.

Project leader **B. P. Barkanov**

APPENDIX II
Excerpts from RTG Prototype Tests

All-Russian Scientific Research Institute of Experimental Physics
(RFNC-VNIIEF)

Development of a Low-Power Radioisotope Thermoelectric Generator (RTG) to Support Remote Monitoring Systems for Nuclear Material Storage Facilities

RTG PROTOTYPE TESTS

Report on task 10 (contract BF-1481)

Project leader
B. P. Barkanov

Sarov
2001

This paper indicates the completion of RTG prototype tests in accordance with task 10 under contract BF-1481 between Sandia National Laboratories and VNIIEF.

RTG experimental prototypes (serial numbers 01 and 02) were subjected to the testing on compliance with technical and operational requirements of Task Order for research and development of RTG 238-0,01/3. The test results prove adequacy of the RTG selected design and technical solutions.

Positive results of the testing [1] enable us to consider that we are ready to start production of radioisotope heat source (RHS) and RTG based on the design and technological documentation.

In accordance with task 10 the Contractor shall provide Sandia with the test protocol and a video of the RTG prototype tests.

As it was mentioned in the report on task 9 [2] a video of the RTG test was a part of the video made under task 9.

The RTG prototype test protocol is submitted to SNL with this report.

. Protocol of the RTG 238-0,01/3 (serial numbers 01 and 02) prototype tests

2. "RTG prototype production" - report on task 9 under the SNL contract BF-1481

TEST PROTOCOL
for the RTG 238 – 0,01/3 (serial numbers 01, 02)
experimental prototypes

According to task 10 under the contract BF-1481 and based on additional agreement #3-00 to contract #06-99/01/3242K of 30.07.99 Electromechanical plant Avangard in cooperation with RFNC-VNIIEF carried out the RTG 238-0,01/3 experimental prototypes (serial numbers 01 and 02) testing. The testing are based on the agreed upon Test Program and Procedure on compliance with technical and operating requirements AVE 2PM.

1. Test specimen

Based on design documentation AVE2 two RTG 238-0,01/3 experimental prototypes were manufactured. The RTG 238-0,01/3 prototype (serial number 01) includes a radionuclide heat source AVE 2.100 of 1.43W and a semiconductor thermoelectric battery STB-0,01/3 (serial number 01) having 245 working couples from 250 thermocouples.

The RTG 238-0,01/3 experimental prototype (serial number 02) includes a radionuclide heat source AVE 2.100 of 1.38W and a semiconductor thermoelectric battery STB-0,01/3 (serial number 02) having 235 working couples from 250 thermocouples.

The STB installed in the RTG experimental prototypes has the following dimensions: 11.7x11.7x20 mm. The arm section is 0.4x0.38 mm. The STB is fabricated from high-alloy, high-temperature material based on bismuth, antimony and selenium tellurides for a 150°C average temperature. The semiconductor thermoelectric battery STB-0,01/3 is made in accordance with drawing documentation eI5.866.021.

In accordance with AVE 2PM test program the RTG 238-0,01/3 experimental prototype (serial number 02) was subjected to testing on compliance with technical and operating requirements. The RTG experimental prototype (serial number 01) was subjected only to testing on compliance with technical specification (excluding testing under temperature difference from -20°C to +60°C).

2. Test objective

2.1. Test the RTG 238-0,01/3 experimental prototype compliance to the technical and operating requirements of the Statement of Work.
2.2. Assess experimental adjustment of the RTG-238-0.01/3 and its components, design documents before starting prototype production.

3. Test scope

Based on the requirements of the Statement of work the RTG technical specifications and operating impacts are split into two blocks. Thus, the RTG testing is carried out in two regimes to confirm the RTG technical specifications and its resistance to the operating conditions.

3.1 Testing to confirm technical features:

The RTG outer surface radioactive containment control
Control of radiation equivalent dose power
The RTG output electric power measurement (beginning of the service life)
The RTG output electric power at the end of the service life
Test of the RTG electric power under temperature difference from -20°C to +60°C
The RTG operation justification during the set service life
The RTG actual mass measurement
Measurement of the RTG dimensions

3.2. Testing on resistance to operating environment:
Testing of the RTG operation at a relative humidity up to 98% and at a temperature of 35°
Testing of the RTG operation under temperature difference from -50°C to +50°C
Testing of the RTG operation at a pressure of 50KPa – 150KPa (375 – 1125 mm of mercury)
Testing of the RTG operation at an operation temperature of 25°C
Testing of the RTG operation at a temperature of -20°C to +80°C
The RTG sinusoidal vibration test at a frequency of 25Hz, overloading of 2g for 0.5 hours
Testing of the RTG operation under transportation shocks

4. Test results

4.1 The RTG outer surface radioactive containment control
The RTG-238-0.01/3 (serial numbers 01, 02) outside surface is checked for radioactive containment by a smear method. The method is based on identification of radioactive activity of the material removed from the RTG surface using a spirit-wet coarse calico tampon. Ethyl alcohol is an effective surface-active material that allows the average coefficient of radioactive substance removal to be increased up to 90%.
Smear activity is measured using α-radiometer of a "SPAR".
The RTG outer surface must not be radioactive polluted. It was proved that the outer surface of the prototypes (serial numbers 01 and 02) was not polluted.

4.2. Control of radiation equivalent dose power

Actual (natural and man-caused) gamma (exposure doze mrad/h) and neutron (μSV/h) radiation background are measured in the industrial rooms.

The RTG-238-0.01/3 experimental prototype is placed on the working table and photon exposure rate is determined at a distance of 1 m from the outside (cylindrical) surface. Photon exposure rate is equal to the obtained value minus photon radiation background value.

The RTG neutron radiation equivalent dose power is measured at the same point. The neutron exposure rate is equal to the obtained value minus the value of the background.

Photon exposure rate is measured using a DRG-01T1 dosimeter. The neutron exposure rate is determined with the help of DKS-96 dosimeter-radiometer with a BDMN-96 detection block.

The power of ionizing radiation equivalent dose is calculated.

$$D=0.962P + Q,$$

where D – power of ionizing radiation equivalent dose, μSv/c, (mrem/h);

0.962 conversion factor from photon exposure rate to fell equivalent dose power;

P photon exposure rate at a 1m-distance;

Q – neutron radiation equivalent dose power at a 1m-distance.

The ionizing radiation equivalent dose power at a 1m-distance shouldn't exceed 0.028, μSv/c, (10 mrem/h). Actual ionizing radiation equivalent dose power of the RTG serial number 01 is 0.00014 μSv/c, (0.05 mrem/h) and 0.0001μSv/c, (0.036 mrem/h) from the RTG serial number 02.

4.3. The RTG output electric power measurement (beginning of the service life)

The RTG (serial numbers 01 and 02) output electric power is measured on the BF-1481.00E1 test bed.

The ambient temperature is measured in the working room. Using a resistance box select such a total load resistance $R_{L\Sigma}$ when voltage is equal to 3±0.1 V.

$$R_{L\Sigma}= R_L + R_C,$$

where R_L – loading resistance, Ohm,
R_C – resistance of connecting cable, Ohm.
To achieve steady mode (the temperature difference of the hot junction doesn't exceed 2°C/h) loading resistance is corrected using a resistance box in order to hold the output voltage at a level of 3±0.1 V. Changes of output electric power, the hot junction temperature, the temperature of the outside surface of the bottom and the shell are recorded during the tests.
Actual values of load resistance, current and voltage were recorded. The output electric power was determined with the help of the following formula:

$$W=I \cdot U,$$

Where W – output electric power, mW,
I – current, mA,
U – voltage, V.

The RTG output electric power should be no less than 15mW.

The RTG prototype output electric power (serial number 01) was 17.1 mW (fig.1), the hot junction temperature was 130.5°C (fig.2) bottom temperature was 32 °C, and the temperature of the shell was 28.5°C (fig.3). The RTG prototype output electric power (serial number 02) was 15.7 mW (fig.1), the hot junction temperature was 125°C (fig.2) bottom temperature was 28 °C, and the temperature of the shell was 25.4°C (fig.3). The ambient room temperature was 22°C. The difference of the output electric power of the RTG prototypes is connected with different ambient temperatures at different time periods and with negligible gas release from the RTg structure materials.

4.4 The RTG output electric power at the end of the service life

The RTG thermal power will be changed adequately to the law of radioactive decay with respect to plutonium-238.

$$W_\tau = W_0 e^{-\lambda\tau}$$

W_τ - value of thermal power at a τ time,
$W_o = 1.5$ W – the RTG calculated thermal power at the moment of production;
$\lambda = 7{,}9 \cdot 10^{-3}$ 1/year – constant of plutonium-238 decay;
$\tau = 50$ years – the RTG service life

Substituting the appropriate values we get calculated thermal power at the end of the service life (1W).

The RTG output electric power under equal conditions is characterized by a volt-ampere characteristic. Reducing of thermal power increases the STB resistance that results in changing of volt-ampere characteristic parameters. Being operable the RTG from optimized state transfers into non-optimal operation mode. Thermal power dependence of voltage and volt-ampere characteristic can be determined only experimentally that requires significant additional expenditure. The most preferable way is to apply intensifying electronic devices providing the RTG appropriate electrical characteristics at the RTG output.

4.5. Test of the RTG electric power under temperature difference from -20°C to +60°C

From room temperature the RTG-238-0.01/3 (serial number 02) is placed into a temperature chamber "Moroz" with a temperature of -20°C and stabilized at -20°C till the RTG achieves a steady-state operation mode (the change of the hot junction temperature doesn't exceed 2°C/h at the RTG output voltage of 3V). The RTG output electric power and the hot junction temperature changes are recorded during the testing at a BF-1481.00E1 test table.

After the RTG achieves steady operation mode it removed from the temperature chamber "Moroz" and is placed to the desiccator and the ambient temperature is gradually raised to 60°C with a ~2°C/min speed. The maximal transfer time from the temperature chamber to the desiccator is 3 minutes. The RTG is stabilized till it achieves a steady operation mode while the changes of the hot junction temperature and the output electric power are recorded at the output voltage of 3V.

The RTG loss of electric power at a temperature of -20°C and +60°C should not exceed 10% from nominal value after achieving a steady-mode. Actual loss of the output electric power up to 10% from nominal value is obtained at a temperature of 60°C (fig.4). The temperature change of the hot junction and the environment is shown on figure 5.

4.6. The RTG operation justification during the set service life

It is a particular feature of the RTG-238-0.01/3 that its service life period is 50 years. There is no analogue in the world practice. It is a challenge to justify express methods for service life conformation, as a great number of independent factors should be considered. They are the following: daily temperature change, gas separation from structural materials, changes in physical mechanical properties of structural materials due to their temperature-time aging, compatibility of structural materials and some other factors. Heuristic method of the RTG-238-0.01/3 service life conformation seems to be the most acceptable. It is based on the common sense and actual experience in the field of operation of similar types of various-purpose RTGs.

The report on task 2 under contact BF-1481 contains a review of known RTG designs. The review includes shortcomings and advantages of the known RTG designs. Based on the review an RTG-238-0.01/3 design is selected. This optimal design includes radionuclide heat source based on plutonium-238 (half life is 87.7 years) as a fuel element. A semiconductor thermoelectric battery based on monolithic thermoelectric blocks produced by micro module technique from low-temperature thermoelectric materials based on solid solutions of binary compounds Bi_2Te_3, Bi_2Se_3, Sb_2Te_3, is used as an energy converter. The solid compounds provide small sizes, high mechanical strength and maximal conversion efficiency of the blocks. The design also includes solid thermal insulation ATM-17 based on A-380 aerosil with quartz fiber, chrome oxide and phenol resin as a heat-insulating material. All the described factors allow a 50-year service life to be justified.

4.7. The RTG actual mass measurement

According to the "Statement of work on research and development of RTG-238-0.01/3" mass requirements are not developed.

The RTG-238-0.01/3 actual mass is measured using balance with an error of 0.1 gr. The RTG 238-0,01/3 serial number 01 mass is 425,5 g, while the RTG serial number 02 mass is 431.5 g.

APPENDIX III
Final Report

RUSSIAN FEDERAL NUCLEAR CENTER

ALL-RUSSIAN SCIENTIFIC RESEARCH INSTITUTE OF EXPERIMENTAL PHYSICS

(RFNC-VNIIEF)

Low-Power Radioisotope Thermoelectric Generator (RTG) to Support Remote Monitoring Systems for Nuclear Material Storage Facilities

FINAL REPORT ON CONTRACT BF-1481

Report on task 11 under the SNL contract BF-1481

Project lead ____________ **B. P. Barkanov**

" " ____________ **2001**

Sarov

2001

CONTENT

List of Acronyms

SW – statement of work
RTG – radioisotope (radionuclide) thermoelectric generator
RHS – radionuclide heat source
STP – semiconductor thermoelectric pile
TMU – thermoelectric micro-module unit
TI – thermal insulation
TT – thermoelectric transformer
SVTI – screen-vacuum thermal insulation
SCC – standard climatic conditions

Introduction

The electronic and electrical devices that are integral to remote monitoring systems for long-term nuclear material storage facilities must have stable, safe and secure, highly reliable power sources requiring little or no maintenance and having a long life. Power sources that have such characteristics will increase facility security while minimizing the affects related to events such as loss of power or accidental power disconnects. Long-term safe power sources enable facility operators to minimize maintenance operations, which reduces facility access and radiation exposure.

The objective of the project is to create a low-power radioisotope thermoelectric generator (RTG) to support the monitoring devices of the remote monitoring system, which voltage is $\cong 3V$ under power consumption of $\leq 10mW$.

The Goals for the Low-Power RTG Development Project are to:

develop RTG technical and operating requirements;
review and document relevant information on existing RTG designs and performance;
develop an optimal RTG design;
perform theoretical investigations of the RTG thermal parameters and electric characteristics;
produce a RTG;
assembly experimental and test complexes to test the RTG mockup and experimental models;
perform computation-experimental research of the RTG;
develop design documentation for the RTG experimental prototype;
produce two optimized RTG prototypes and a demonstration model;
test the RTG experimental prototypes;
submit final report on the work performed under the project.

Task 1: Technical and operating requirements for the RTG [1]

Statement of work [1] agreed upon with developers of electronic equipment was based on the Contract requirements and the RF existing standards on RTG development and testing (GOST 18696-90 "Radionuclide thermoelectric generators. Types and general requirements", GOST 20250-83 "Radionuclide thermoelectric generators. Acceptance procedure and test technologies".

The Statement of work identifies the RTG technical requirements. Among them are the following:

1.1. Specifications

1.1.1. RTG output electric power at the beginning of service life is 0.015 W (min.) under voltage of 3V.

1.1.2. RTG output electric power at the end of service life 0.010 W (min.) under voltage of 3V.

1.1.3. RTG service life from the moment of acceptance at the manufacture plant including storage, transportation, installation, check work and active operation in work mode – 50 years

1.1.4. RTG mass – disabled

1.1.5. RTG sizes and dimensions, mm

- Diameter – 60
- Height – 70

1.2. Requirements for the RTG construction

1.2.1. RTG should include the following parts

- Radioisotope heat source (RHS)
- Thermoelectric unit
- Thermal insulation
- Insulated external power enclosure
- Packaging.

1.2.2. RTG will be a mono unit without elements mounting to the power consumer

1.2.3. RTG will be non-separable and non-repairable

1.2.4. One of the principle parts of RTG is RHS including an active part in the form of fuel pellet based on Pu-238 dioxide and shielding providing sealing of the active part under the operating and accident conditions.

RHS sizes and dimensions, mm

- Diameter – 17
- Height – 22

RHS heat rating – 2.5 W (max.)

1.2.5. Thermoelectric unit will include the following:

- Semiconductor thermoelectric battery (STB)
- Components to connect STB to RHS and RTG casing
- Electric outlets

1.3. Safety requirements

1.3.1. The RTG should meet the following safety requirements in accord with GOST 18696-90:

Radiating power at the package surface should be maximum 0.56 (200) μSv/s (μrem/h) and at a distance of 1m from the package surface the radiating power should be maximum 0.028 (10) μSv/s (μrem/h);

The RTG outer surface should not be contaminated with radioactive materials; during operating, storage and transportation the RTG should not evolve any substances into the environment;

Any RTG spontaneous failure should not result in changing of the RTG parameters impacting the ecology;

The RTG design should satisfy requirements of the existing "Safety regulations for radioactive material transportation" (PBTRV-73), "General nuclear safety regulations for fissile material utilization, reprocessing, storage and transportation" (PBYa-06-00-96), "Radiation safety standards" NRB-76/78, "General sanitary rules for handling with radioactive materials and other sources of ionizing radiation" OSP-72/87;

The RTG design should provide the RTG protective properties after any accidental impacts.

1.3.2. General RHS safety requirements and concerns

RHS air-tightness should not be damaged under the impact of internal pressure of radiogenic helium under operating conditions.

RHS should be sealed under the impact of STB material melt during a fire.

RHS being a radioactive substance of a specific type should meet the following safety requirements in accord with "IAEA Regulations for radioactive material safe transportation" and GOST R50629-93 "Radioactive material of specific type. General technical requirements and test technologies":

Drop RTG from 9 m onto a target, made from low-carbon steel with thickness at least 12 mm, that steel is snug against the surface of a concrete block and the mass of the steel should be at least 10 times that of the specimen for the test. The square of the target shock surface should not be less than 2 RTG base surface in the packaging. The shock surface should be horizontal.

- Drop RTG from 1m onto a bar made from low-carbon steel. The bar diameter is 150±5 mm. The bar should bulge out the target surface at 200 mm.

Thermal impact at a temperature of 800±40°C (1073±40 K) for half an hour.

Task 2: Review of known RTG designs [2]

Task 2 was aimed at performing an analysis of known RTG designs that meet general requirement of the statement of work. The analysis proves that there are no such developments in the world. The existing items-analogues have the service life of 10-15 years. The real operation experience and actual operation life of hundreds of RTG of the similar type and various purposes utilized as fuel element (RHS) based on plutonium 238 (Pu-238 half-life is 87.7 years) enable us to consider the task to be feasible. The developed and produced RTG with the closest characteristics to the expected ones are the following: "RITM-MT", "RITM-C-01", "RITM-C-02", "Grunt-1", etc. These items have high power-consuming values, great potential for safe and maintenance-free life, and provide radiation and ecological security under possible accidents during the storage, transportation and operation.

Moreover, high characteristics of the above devices are proved by long-term application of such RTGs. In this connection the above RTGs are approved to be analogue to make an overview of the technical solutions in the RTG designs.

Principal technical and operation characteristics of "RITM–MT", "RITM-C-01", "RITM-C-02", and "Grunt-1" are described in [2] and in table 1.

As appears from the above table, the characteristics of the RTG designs under consideration in spite of their closeness to the given ones do not allow us to use any design to solve the task. The two-channel RTG "RITM-C-02" has the closest parameters to the required characteristics, so this design should be thoroughly analyzed.

Table

The principal technical and operating characteristics of milliwat -power RTG

Parameters	RTG type			
	Г-238- -0,001/0,5 RITM-MT	Г-238- -0,0025/2,5 RITM-C-01	Г-238- -0,02/3 RITM-C-02	Г-238- 0,05/12 Grunt-1
Output electric power, mW, min	1,0	2,5	20,0	50,0
Nominal voltage, V	0,5	2,5* (1,25+1,25)	3,0* (1,5+1,5)	12,0
RHS thermal output, W	0,22	0,6	1,6	3,5
RHS-238 dimensions, mm - diameter - height	 10,0 12,5	 7,5 15,2	 12 20	 20 30
RTG dimensions, mm: -diameter - height	 22 50	 40x25x12	 25 70	 65 120
Mass, g, max	50	50	100	1000
Power of the equivalent dose of neutron and gamma radiation at a distance of 20 sm. from the RTG surface in the open air, mrem/h, max	0,1	0,25	0,8	2,1
Service life, years, max	10	10	10	10

RTG efficiency, %	0,5	0,7	1,3	1,7
Operating range of environmental temperature	+10°C up to +45°C	(-50°C) up to +65°C	(-50°C) up to +80°C	(-60°C) up +65°C
Reliability	0,99 (0,8)	0,99 (0,8)	0,99 (0,8)	0,9 (0,8)
Year of development	1975	1977	1980	1982
Type of thermal insulation	SVTI with xenon			ATM-17

* RTG has two independent channels

"RITM-C-02" RTG design is shown on figure 1. Upper cover 2 made of 12X18H10T steel and low cover3 made of 29HK Kovar are welded to the flanges of sealed cylindrical casing 1 made of 12X18H10T steel using argon-arc technique. RHS 4 is placed into heat-conducting copper vessel 5, which fastened to the micro-module STP flange 6 using firm cantilever scheme. In its turn, this assembly is strengthened to the low cover by the second STP flange. Both joints 7 are made by BK-9 glue with additions increasing heat conductivity. To increase resistance to the flank mechanical impacts the STP and cover adhesive joint is made in the form of truncated cone. Radiator 9 removes heat from low cover and at the same time it protect exhaust tube 10 and hermetic electric outlets 11 from mechanical damage. STP-RHS cantilever is protected by screen thermal insulation 8 made of SVTI material. RTG cavity is filled with xenon. Sealed electric outlets are made of Kovar and soldered into the cover using molybdenum glass.

"Grunt-1" RTG is shown in figure 2. It includes the following: casing 1; upper cover 2 with radiator 4; low cover 3; STP 5; RHS 6 in the heat-conducting vessel 7; thermal insulation 8; elastic heat transfer 9; exhaust tube 10; electric outlets 11.

The principal difference of "Grunt-1" RTG design from RTGs of "RITM" type is that solid insulation ATM-17 is used in this construction. Here thermal insulation is a carrier and increases the strength of cantilever scheme of the energy transformation unit assembly. The availability of elastic heat transfer 9 and adjusting device 12 allows STP to be mechanically unloaded from the flank while maintaining efficient heat removal from cool seals to the radiator. This construction applies standard sealed electric outlets soldered into the cover.

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